Heat Transfer Simulation Report

Anish Kumar Sahu
Roll No: 210100015

April 9, 2025

Objective

To simulate and compare the temperature distribution on an iron plate subjected to a moving heat source, modeled both as a point source and a line source. The simulations are performed for different plate thicknesses and laser parameters to analyze the temperature profile and valid processing regions.

Code

```
# import numpy as np
import matplotlib.pyplot as plt
from scipy.special import kv  # Modified Bessel function K0

# Material Properties: Iron
rho = 7800                # kg/m^3
cp = 450                  # J/kg K
k = 80                    # W/m K
alpha = k / (rho * cp)    #  m  /s
T_amb = 300               # Initial temperature (K)
T_melt = 1811             # Approx. melting point of iron (K)
T_boil = 3134             # Approx. boiling point of iron (K)

# Heat Source Characteristics
eta = 0.6               # Efficiency (Fresnel-adjusted)
q_pulse = 800           # J/m   (Fluence)
pulse_duration = 8e-8   # s
q_max = q_pulse / pulse_duration

# Laser Parameters (can be varied)
laser_power = 1000      # W
scan_speed = 0.05       # m/s

# Spatial Evaluation Settings
```

```python
y_eval = 1e-3              # Evaluate 1 mm off center line
x_eval = 0                 # On centerline

# Plate Thicknesses
thin_h = 0.001             # 1 mm
thick_h = 0.010            # 10 mm

# Temperature Estimation Models

def point_heat_temp(power, speed, x, y, z, k, alpha, T_base):
    heat_input = eta * power
    r = np.sqrt(x**2 + y**2 + z**2)
    r = max(r, 1e-6)  # Avoid divide-by-zero
    decay = np.exp(-speed * (r + x) / (2 * alpha))
    return T_base + (heat_input / (2 * np.pi * k * r)) * decay

def line_heat_temp(power, speed, thickness, x, y, k, alpha, T_base):
    heat_input = eta * power
    r = np.sqrt(x**2 + y**2)
    r = max(r, 1e-6)
    arg = speed * r / (2 * alpha)
    if arg > 700:  # Avoid overflow
        return T_base
    decay = np.exp(-speed * x / (2 * alpha)) * kv(0, arg)
    return T_base + (heat_input / (2 * np.pi * k * thickness)) *
       decay

# Max Temperature vs Plate Thickness for Both Sources

def plot_max_temp_vs_thickness():
    thicknesses = np.linspace(0.001, 0.01, 100)  # 1 mm to 10 mm
    line_temps = [line_heat_temp(laser_power, scan_speed, h, 0, 0, k
       , alpha, T_amb) for h in thicknesses]
    point_temps = [point_heat_temp(laser_power, scan_speed, 0, 0, h,
        k, alpha, T_amb) for h in thicknesses]  # max over z

    plt.figure(figsize=(10, 6))
    plt.plot(thicknesses * 1e3, point_temps, 'o-', label='Point Heat
        Source (Max over z)', color='blue')
    plt.plot(thicknesses * 1e3, line_temps, 'o-', label='Line Heat
       Source', color='orange')
    plt.axhline(T_melt, color='red', linestyle='--', label=f"Melting
        Point ({T_melt} K)")
    plt.axhline(T_boil, color='green', linestyle='--', label=f"
       Boiling Point ({T_boil} K)")
    plt.xlabel('Plate Thickness (mm)')
    plt.ylabel('Maximum Temperature (K)')
```

```
    plt.title('Maximum Temperature vs. Plate Thickness\nNd:YAG, P = 1000 W, u_x = 50 mm/s')
    plt.legend()
    plt.grid(True)
    plt.tight_layout()
    plt.show()

# Plot Temperature Surface for Both Models

def plot_3D_profiles():
    x_range = np.linspace(-0.005, 0.005, 50)
    y_range = np.linspace(-0.005, 0.005, 50)
    X, Y = np.meshgrid(x_range, y_range)

    for h, label in zip([thin_h, thick_h], ["1 mm", "10 mm"]):
        Z_point = np.zeros_like(X)
        Z_line = np.zeros_like(X)

        for i in range(X.shape[0]):
            for j in range(X.shape[1]):
                Z_point[i, j] = point_heat_temp(laser_power, scan_speed, X[i,j], Y[i,j], 0, k, alpha, T_amb)
                Z_line[i, j] = line_heat_temp(laser_power, scan_speed, h, X[i,j], Y[i,j], k, alpha, T_amb)

        # Plot point source
        fig1 = plt.figure(figsize=(10, 8))
        ax1 = fig1.add_subplot(111, projection='3d')
        ax1.plot_surface(X * 1e3, Y * 1e3, Z_point, cmap='hot')
        ax1.set_title(f"Moving Point Source (Plate Thickness = {label})")
        ax1.set_xlabel("X (mm)")
        ax1.set_ylabel("Y (mm)")
        ax1.set_zlabel("Temp (K)")
        plt.tight_layout()
        plt.show()

        # Plot line source
        fig2 = plt.figure(figsize=(10, 8))
        ax2 = fig2.add_subplot(111, projection='3d')
        ax2.plot_surface(X * 1e3, Y * 1e3, Z_line, cmap='hot')
        ax2.set_title(f"Moving Line Source (Plate Thickness = {label})")
        ax2.set_xlabel("X (mm)")
        ax2.set_ylabel("Y (mm)")
        ax2.set_zlabel("Temp (K)")
        plt.tight_layout()
```

```python
        plt.show()

# Parametric Range: Speed vs Power for Valid Region

def plot_valid_param_region():
    powers = np.linspace(500, 5000, 40)
    speeds = np.linspace(0.01, 0.1, 40)
    P_grid, V_grid = np.meshgrid(powers, speeds)

    valid_power, valid_speed, valid_temp = [], [], []

    for i in range(P_grid.shape[0]):
        for j in range(P_grid.shape[1]):
            temp = line_heat_temp(P_grid[i,j], V_grid[i,j], thin_h, x_eval, y_eval, k, alpha, T_amb)
            if T_melt <= temp <= T_boil:
                valid_power.append(P_grid[i,j])
                valid_speed.append(V_grid[i,j] * 1e3)  # mm/s
                valid_temp.append(temp)

    plt.figure(figsize=(10, 6))
    if valid_power:
        scatter = plt.scatter(valid_speed, valid_power, c=valid_temp, cmap='viridis', s=50)
        plt.colorbar(scatter, label='Temperature (K)')
        plt.xlabel('Scan Speed (mm/s)')
        plt.ylabel('Laser Power (W)')
        plt.title(f'Valid Parameter Region (T between {T_melt} K and {T_boil} K)\nPlate Thickness = 1 mm')
        plt.grid(True)
    else:
        plt.text(0.5, 0.5, "No valid parameters found", ha='center', va='center')
    plt.tight_layout()
    plt.show()

# Run All

if __name__ == "__main__":
    print("Generating max temp vs thickness graph...")
    plot_max_temp_vs_thickness()

    print("Generating 3D temperature fields...")
    plot_3D_profiles()

    print("Generating valid parameter map...")
    plot_valid_param_region()
```

Results and Discussion

1. Maximum Temperature vs. Plate Thickness

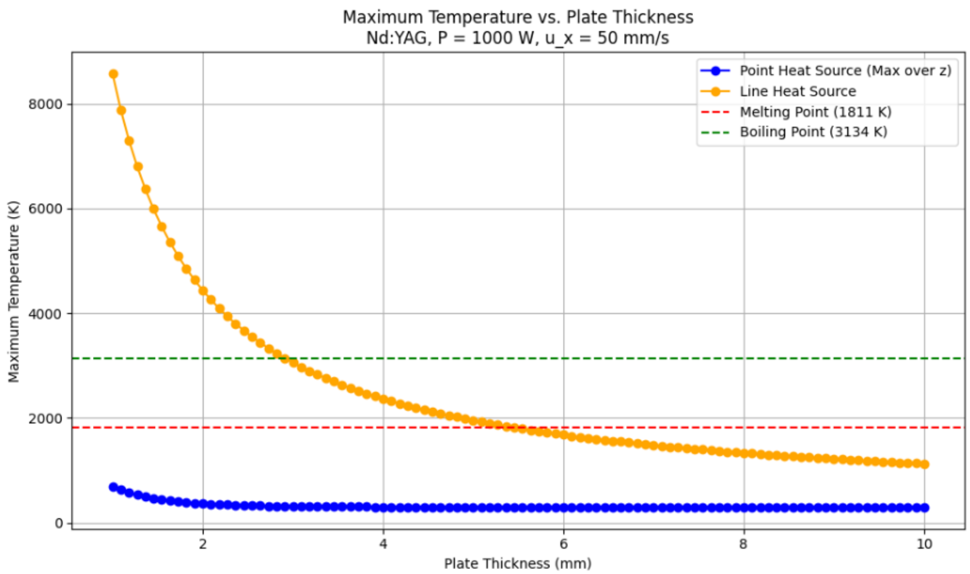

Figure 1: Maximum Temperature vs Plate Thickness for Point and Line Heat Sources

2. 3D Temperature Distribution

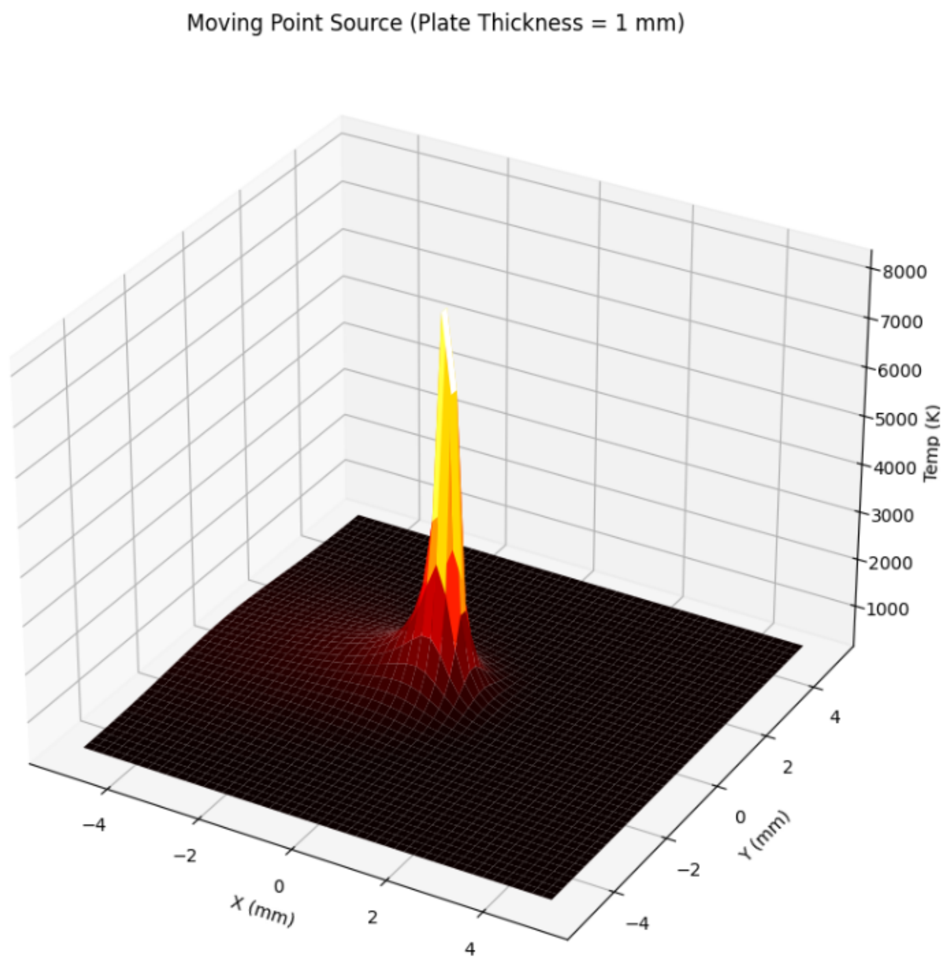

Figure 2: 3D Temperature Profile for Point Source (1 mm Thickness)

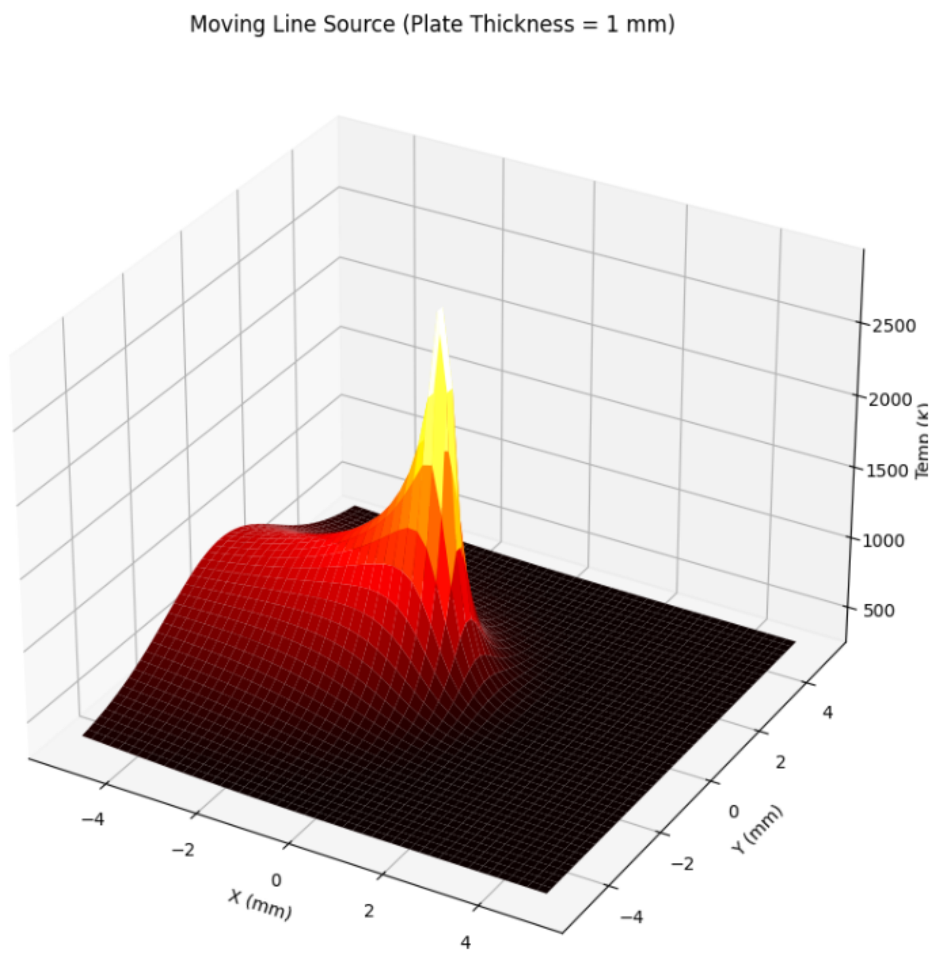

Figure 3: 3D Temperature Profile for Line Source (1 mm Thickness)

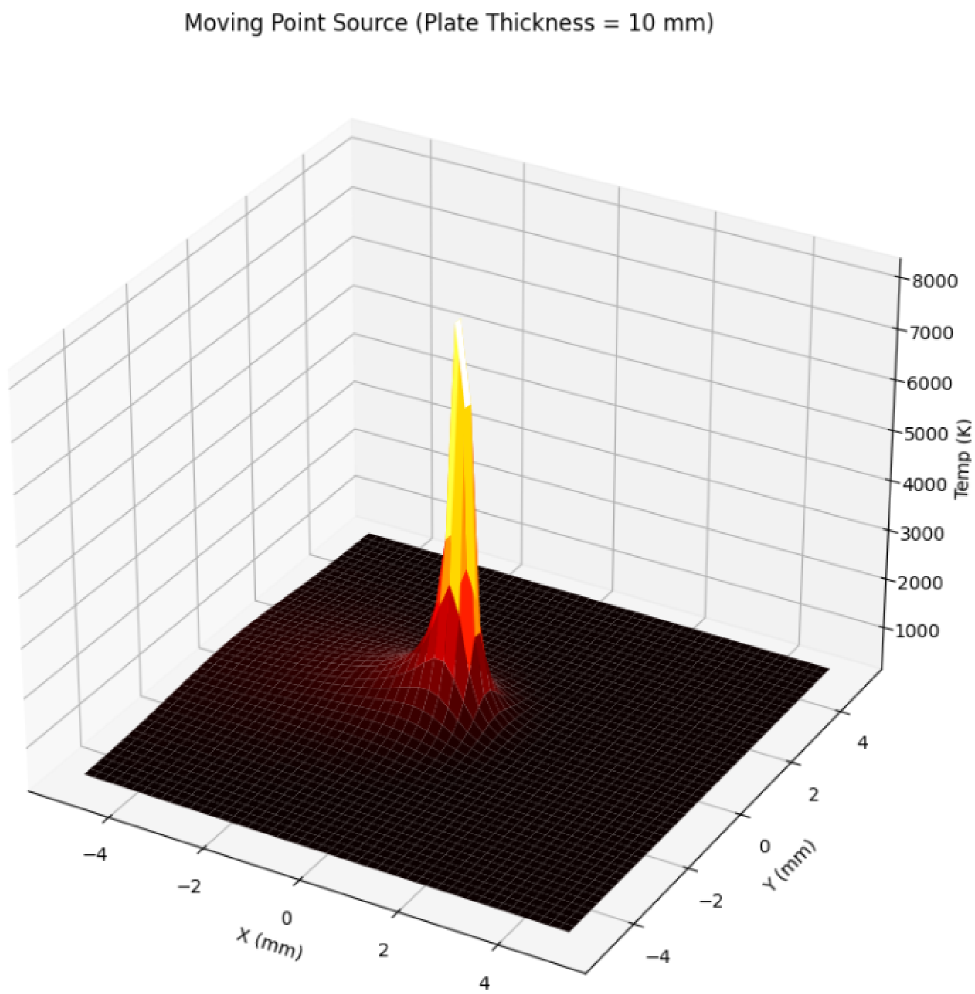

Figure 4: 3D Temperature Profile for Point Source (10 mm Thickness)

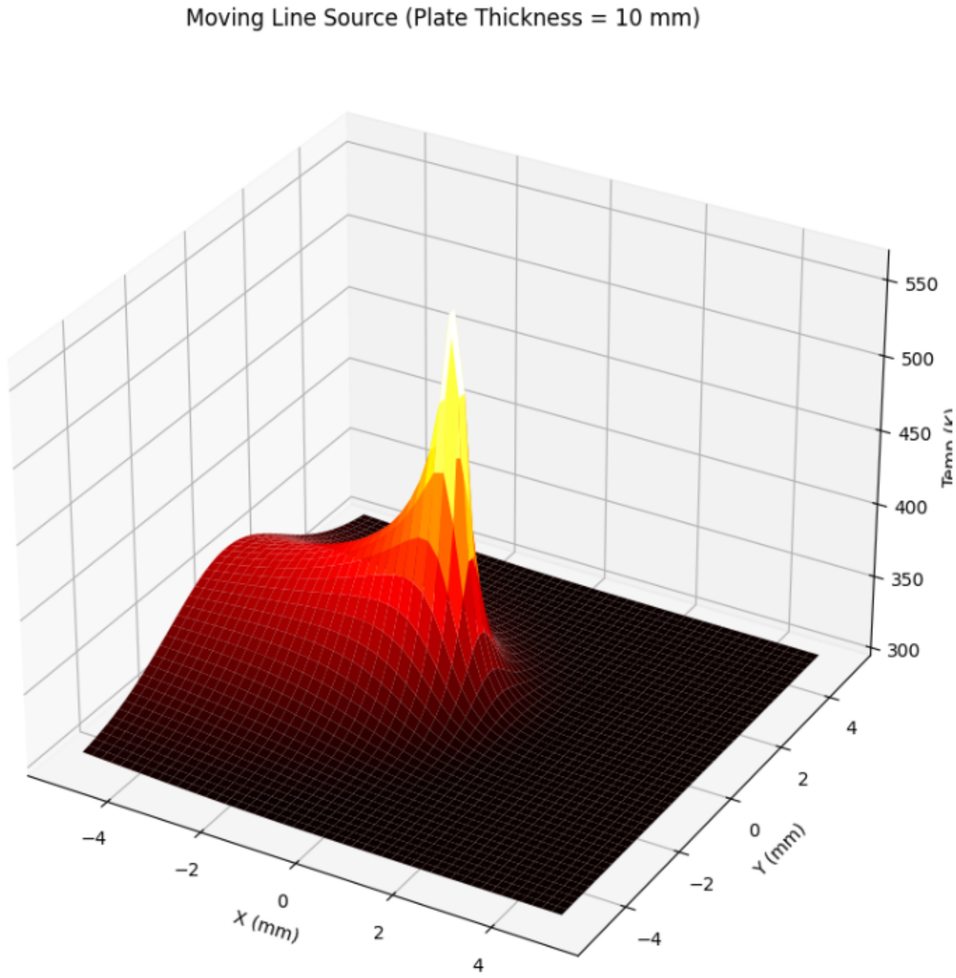

Figure 5: 3D Temperature Profile for Line Source (10 mm Thickness)

3. Valid Parameter Region

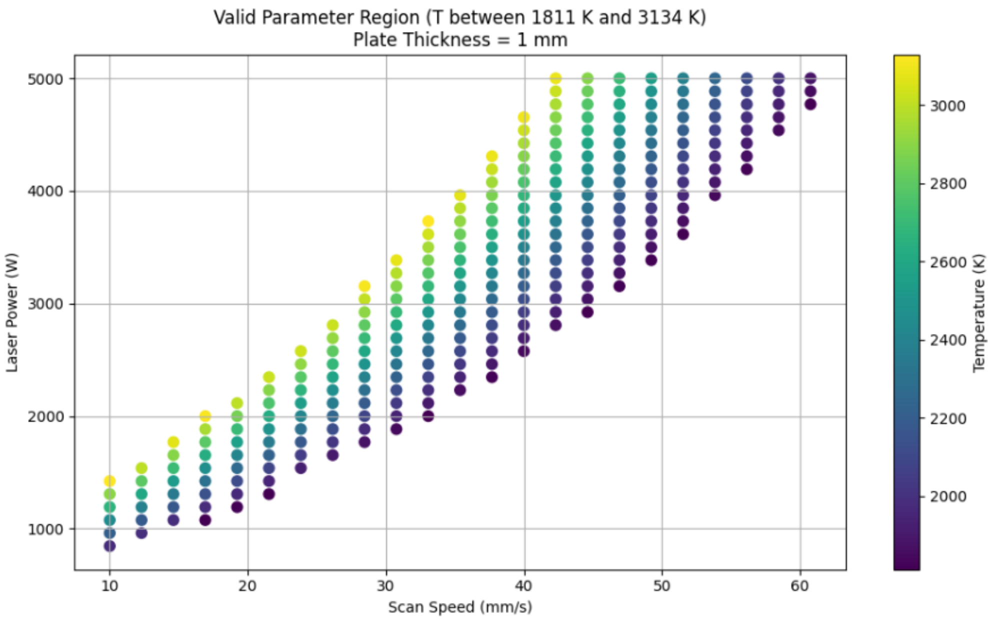

Figure 6: Valid Power-Speed Region (Temperature between Melting and Boiling Point)

Conclusion

The simulation effectively models the heat distribution from moving laser sources on an iron plate. It reveals how plate thickness affects peak temperature and how different parameters like power and speed can be optimized to achieve the desired temperature range without causing melting or boiling.